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Advanced Materials and Manufacturing Technology Developments for Extreme Environment Gas Turbine Applications

Reference

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ABSTRACT

Electrical power generation is becoming increasingly reliant on gas turbines with multiple fuel capability, with research advances focusing on increased efficiency/power output and reduced emissions. Increasing gas turbine efficiency primarily requires higher operating temperatures and reduced coolant flow in the turbine flow path, which makes it challenging to increase component performance, as these will encounter high stresses and large temperature gradients. Current nickel-based alloys, which operate at operate at extreme environments, are exposed to stress caused by temperature or static/dynamic loading like creep and fatigue, oxidation and corrosion, wear, and damage due to vibrations. Higher turbine inlet temperatures are currently managed with internal/film cooling and thermal/environmental barrier coatings for hot section parts. Comprehensive solutions are needed to translate to achieve ultrahigh efficiencies, lower parts cost, reduced scrape rate, and life cycle savings. The paper discusses material developments coupled with innovative manufacturing approaches to be married with advanced design strategies to realize the needed improvements for hot gas path components. The case studies for combustion and turbine components will be presented to demonstrate the structure property relationships and improved component performance at lower cost.

Keywords

gas turbines, materials, coatings, superalloys, additive manufacturing

Introduction

Industrial gas turbines play a major role in power generation providing a clean, reliable and efficient means of producing electricity.[1] Gas turbines have an advantage over many alternative forms of power generation equipment in that they can quickly provide power

during times of peak demand. Unlike commercial aircraft engines, which operate at peak power only during take-off and landing, industrial gas turbines may operate continuously at base load for many thousands of hours.

Industrial gas turbines for power generation are operated in either simple cycle, in which the gas turbine alone is used to drive the generator, or in combined cycle, in which the gas turbine generates power in combination with a steam turbine. Modern combined cycle power plants can achieve efficiencies in excess of 62 %. Although gas turbines operating in simple cycle are less efficient, with thermal efficiencies between 35 % and 45 %, they have greater operational flexibility including shorter start times (achieving full power in as little as 10 min), load following (ability to increase or decrease power output as the demand for electricity changes), and cyclic capabilities (typically operating only during periods of peak demand, often starting to meet peak demand, and then shutting down as demand decreases, e.g., overnight).[2–4] Gas turbines operating in simple cycle are favored for their ability to provide power during periods of high demand (peakers) and, more recently, for balancing power demand with renewable energy sources, e.g., solar and wind power.

As shown in figure 1, the push to higher firing temperatures, increased efficiencies, reduced emissions, and multiple fuel capability continues to demand more out of the gas turbine design and materials systems capabilities. Although design efforts are different for each section of the gas turbine (e.g., increased pressure ratio for compressor, low Nitrogen Oxide (NOx)/fuel flexibility in combustors and increased inlet temperature/reduced cooling and leakages in the turbine section), materials and materials systems play a central role in the function of the gas turbine, and appropriate materials choices are essential to maximizing gas turbine efficiency and operational longevity.

In order to further push the capability of gas turbine engines for higher efficiency and power generation capacity, advances in material and coating systems will play a pivotal role. In this paper, the multifunctionality of these extreme environment materials is described, together with an overview of the state-of-the-art and expected future challenges. Figure 2 shows the cross-section of a gas turbine hot gas path section with materials and coatings performing the traditional structural, thermal, and environmental functions in the combustor and blade and vane sections.[5] From a materials and design perspective, the combustor and turbine section probably represents the most challenging environment in the gas turbine. The temperature of the working fluid entering the hot gas path frequently exceeds the useful working temperature limit of nickel-based superalloys, and in the most advanced industrial gas turbines, the gas path temperatures can easily exceed the melting temperature of the blade and vane alloys by several hundred degrees Celsius. This demands the use of effective cooling schemes and protective low-thermal conductivity (low-K) thermal barrier coatings.

FIG. 1 Critical development areas for gas turbines to address marker drivers.[4] NG - Natural gas and PR - Pressure ratio.

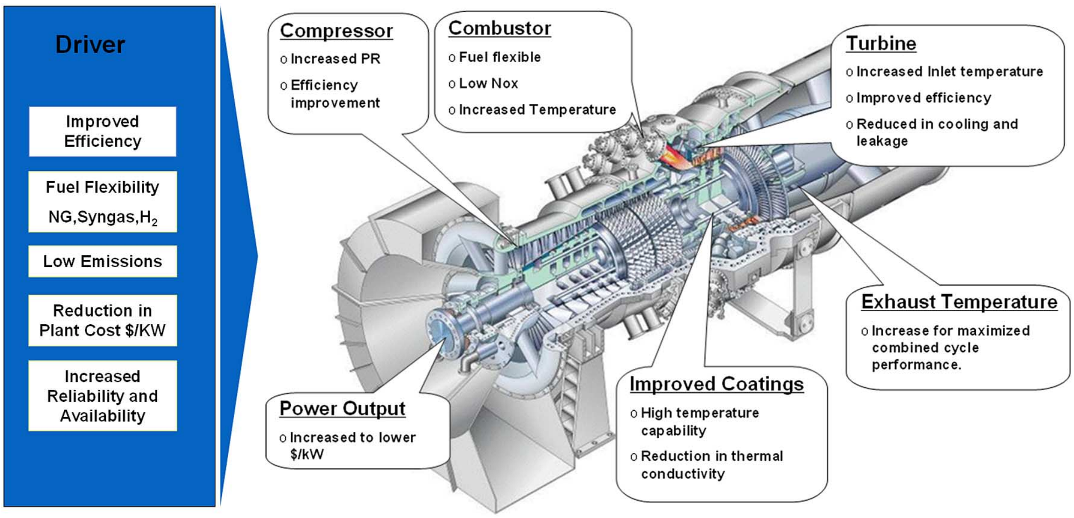
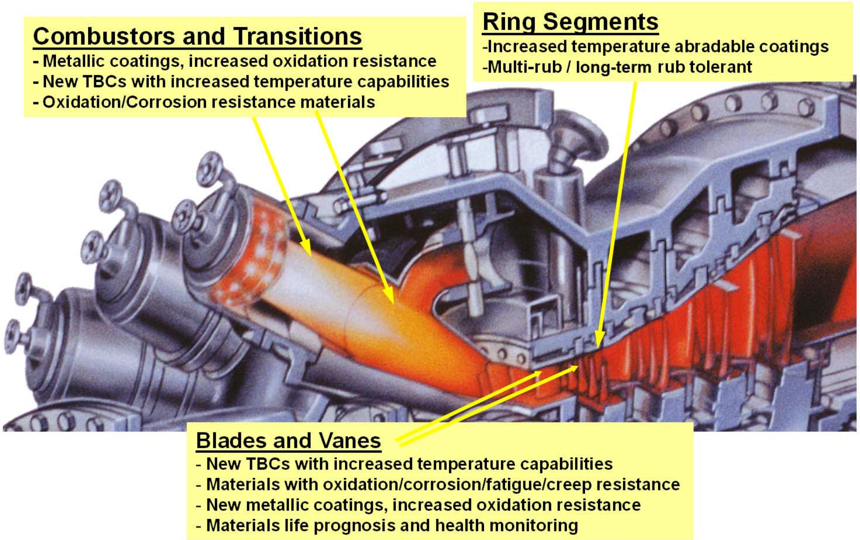


FIG. 2 Gas turbine cut-away showing the different section of the hot gas path with desired materials needs.[5]

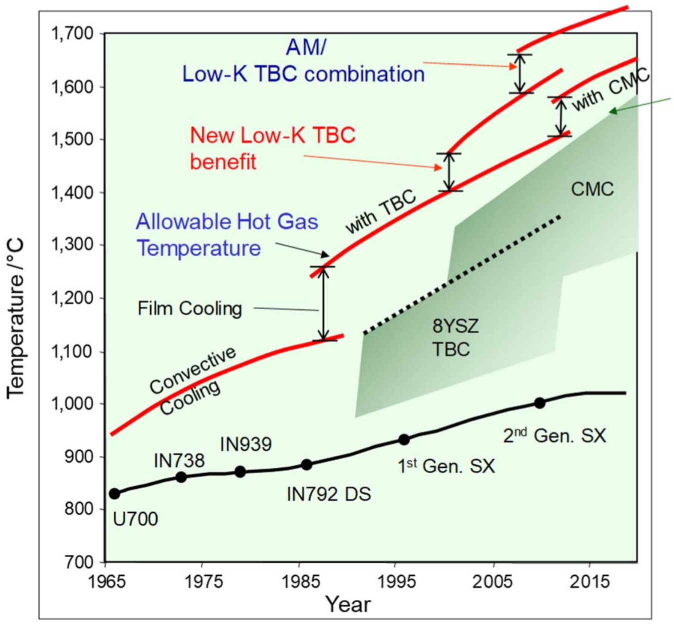


EXTREME ENVIRONMENT MATERIALS

Trends in the development of gas turbines indicate a continuing increase in gas path temperatures, and consequently the thermal barrier coating (TBC) surface temperatures, along with a reduction in cooling air on the internal walls of superalloy components, as shown in **figure 3**. Early developments from 1965 to 2005 have mostly focused on increased durability and extended life of metallic components subjected to high temperatures and high stresses. Nickel-based superalloy components currently in production typically have internal serpentine coolant passages and showerhead film cooling leading edge configurations.[6,7] Higher turbine inlet temperatures are also managed

FIG. 3

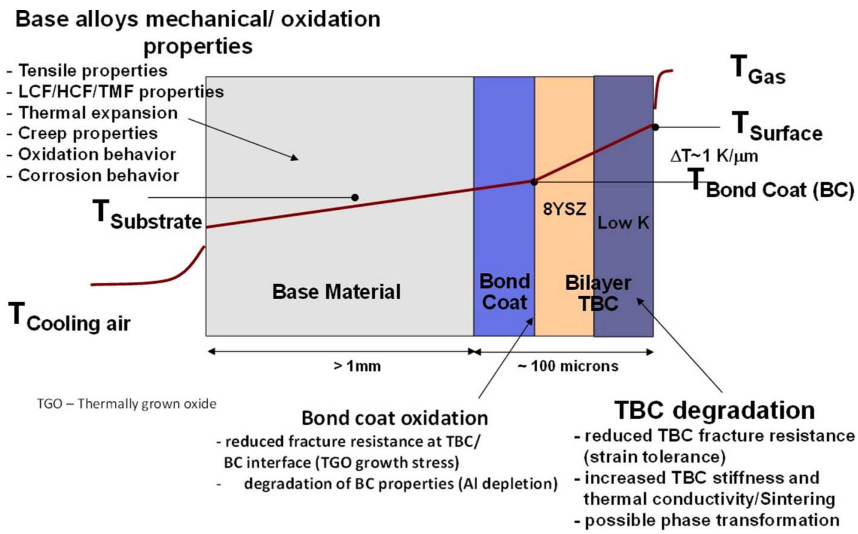
Materials developments to meet the increased turbine inlet temperatures in gas turbines. SX - Single crystal.



with TBCs/environmental barrier coatings for hot section parts (combustors, turbine airfoils, and air seals). These coatings allow increased operating temperature of the engine and therefore enhanced efficiency. Increases beyond 62 % efficiency, however, are hindered by material-property limitations of the current cast nickel-based superalloy components. Existing TBCs, based on 8 wt. % yttria-stabilized zirconia (8YSZ), are susceptible to sintering and phase instability when exposed to temperatures higher than 1,200°C. Advanced low-K TBCs demonstrate 20–50 % lower thermal conductivity than 8YSZ, and their sintering resistances exceed the capability of 8YSZ by almost 200°C to enable higher turbine inlet temperatures, as shown in **figure 3**. This increases the demands on the reliable function of the protective coating system, along with novel component cooling designs, enabled by additive manufacturing (AM). System-level design is therefore required to adapt to the varying thermal and mechanical loads of all cooled hot gas path components. **Figure 3** also shows the alternate path of ceramic matrix composites (CMCs) mostly utilized in aeroengines for stationary components, owing to their high temperature capabilities. However, reliability, processing, and cost challenges remain a barrier for wider applications within the gas turbine.

Figure 4 shows the requirements of each layer in the TBC systems consisting of an oxidation resistant metallic coating, deposited on top of a superalloy substrate, with a porous ceramic coating on top. The structural loading of the components is handled by nickel-based superalloys, which have the necessary properties to tackle the creep, fatigue (high cycle fatigue [HCF] and low cycle fatigue [LCF]), creep–fatigue interactions observed in service. Along with mechanical properties, thermophysical- and oxidation/corrosion-resistant properties also need to be addressed to ensure compatibility with the overlay coatings. The metallic coating performs the dual function of providing adherence of the ceramic coating and additional oxidation resistance to protect the underlying superalloy. Also critical is the strain/thermomechanical fatigue (TMF) cracking of the metallic coatings exposed to cyclic environments. The ceramic coating performs the function of providing thermal insulation to the underlying superalloy and needs to be evaluated for its ability to perform under both the isothermal and cyclic high-heat flux gradient conditions. Phase stability and mechanical properties (strain tolerance/fracture toughness) are also critical for the ceramic coatings because of their exposure to hottest surface conditions within the turbine. The thicknesses of the coatings are almost 1/10 to 1/5 of the superalloy substrate, depending upon the component application. Typically, coatings on blades and vanes are thinner (500–900 microns) compared with those used in combustors (about 1 mm or higher). Although porosity/cracks provide strain compliance, in some instances, a thin dense overlay might be applied for environmental resistance. The characteristics of individual layers (base materials, metallic, and ceramic coating) are described in detail in the following sections.

FIG. 4 Desired system-level characteristics of TBC system for extreme turbine environments.



Nickel-Based Superalloys

Figure 5 illustrates the improvement in the temperature capability of the superalloys,[8,9] showing that the temperature capability has been improved by over 400°C in these 60 years. In terms of substrate properties, superalloys with high chromium content exhibit the best corrosion resistance, whereas superalloys with high aluminum content offer increased oxidation resistance and improved coating compatibility. Nickel-based superalloys containing large amounts of reactive elements contents (e.g., aluminum, titanium) have been cast, wherein the higher aluminum concentration also promotes the precipitation of a strengthening second phase known as gamma prime (γ'). Gamma prime is an intermetallic compound with an ordered crystal structure and a composition based on Ni_3Al. The gamma prime exhibits a yield stress anomaly whereby its strength increases with temperature, and it is this attribute that imparts superalloys with their exceptional high-temperature mechanical properties.[10,11] Achieving the optimum balance between mechanical properties, environmental resistance, and manufacturability is a challenge that attracts significant research and development effort.

Figure 6 shows the possible changes in microstructural features during service in a gas turbine. The complex evolution of microstructure influences mechanical and thermal properties over time, and these changes must be understood to accurately predict material performance and component life.[12] Knowledge of this behavior will aid in gauging the improved temperature capabilities for these alloys.

Cyclic damage in the form of low-cycle or TMF may result from multiple engine starts. TMF damage arises when components are subjected to combined thermal and mechanical loads in which both temperature and stress vary with time. Greater damage often results from TMF than from isothermal fatigue. During engine start-up, local regions of a component heat up at a greater rate than others, for example, the temperature of the outer surface of a turbine blade exposed to the hot gas path heats up more quickly than the cooled internal surface. This leads to a temperature gradient across the wall of the blade. The material on the hot side wants to expand, but it is constrained by the lower temperature material. The thermal strain consequently results in stress build-up in the component. Repeated engine start-up and shut-down cycles result in the accumulation of fatigue damage, which may eventually lead to cracking. A creep component (resulting from extended periods at elevated temperatures and high loads) may also compound the damage experienced under TMF loading conditions. At high temperatures and stresses, the material may undergo stress relaxation and deform under creep. However, when the component cools during engine shutdown, the material is unable to relax, and high residual stress may result.

FIG. 5

Improvement in temperature capability of nickel-based superalloys.[9]

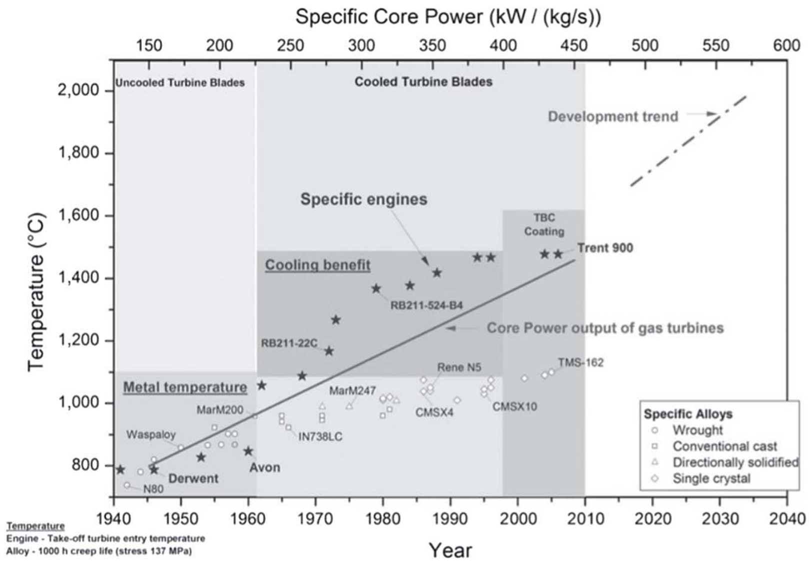


FIG. 6 Microstructural changes in nickel-based alloys over time/temperature exposure.[12] MC - Metal carbides.

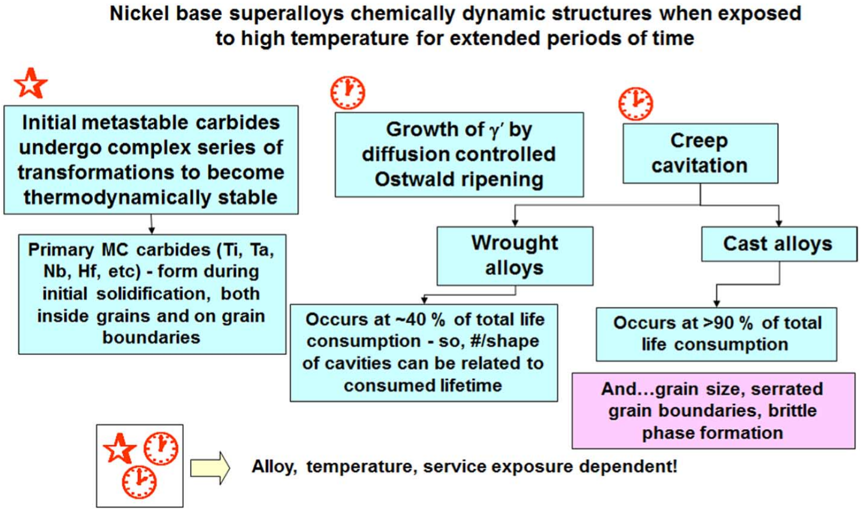
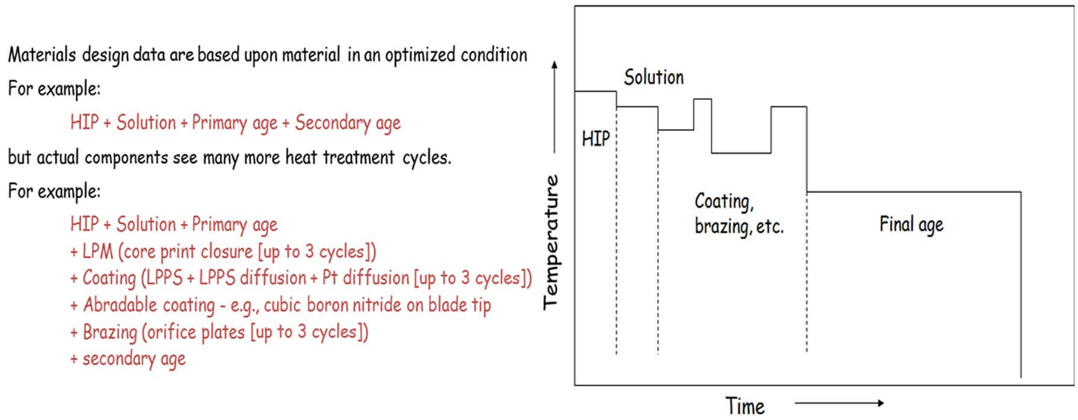


FIG. 7 Variation in manufacturing sequence of components versus cast test slabs. HIP - Hot isostatic pressing, LPM - Low pressure melting, LPPS - Low pressure plasma spraying, and Pt - Platinum.



Gas turbine owners have a desire to extend the life of components to reduce life cycle costs while maintaining safe operating conditions. Life assessment studies incorporating metallurgical and nondestructive testing are performed to assess the potential for the continued operation of components. As a result, the remaining life assessment of these aged units is becoming important for continued safe and reliable operation. The actual components see different variation of heat treatments, based on their conditions—virgin cast or service run repair as shown in figure 7. During operation, these materials undergo different metallurgical degradation processes due to high stress, creep, fatigue etc. So, remaining life assessment of these components/materials is essential for the lifetime extension of these aged units through repair work, continuous inspection, and replacement of the degraded parts.

TBC

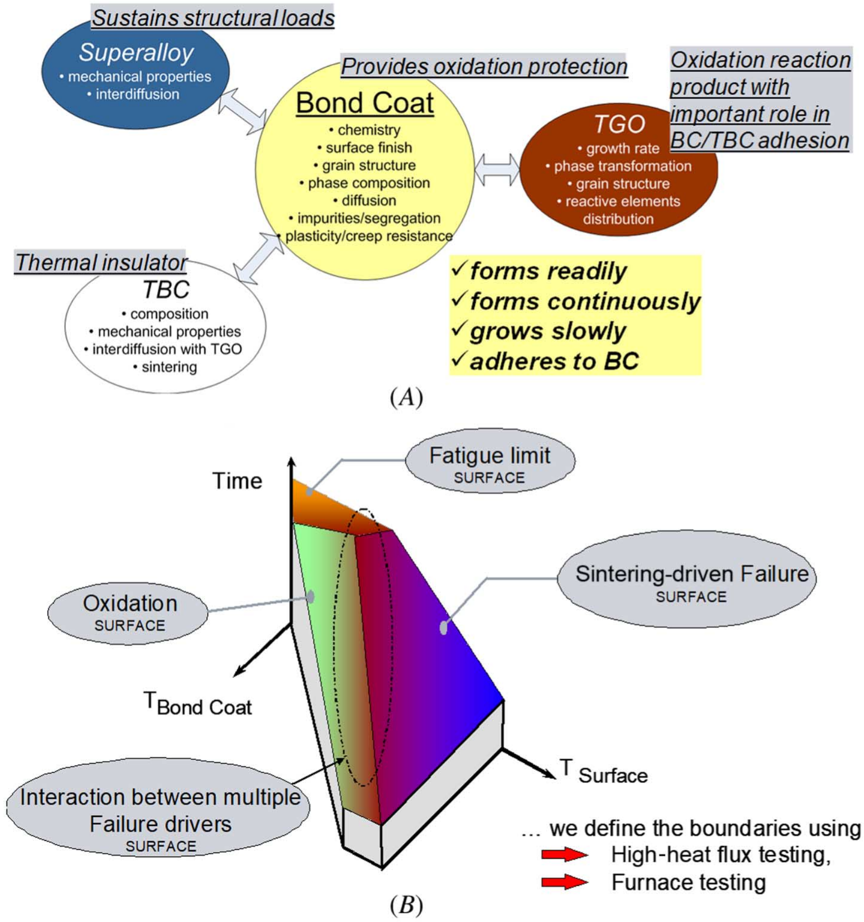
TBCs have been critical to the operation of such gas turbines in aircraft and land-based applications as they provide thermal, oxidation, and hot corrosion protection of high-temperature components.[13,14] TBC systems on superalloy components consist of a metallic bond coat and a top coat consisting of one or more ceramic

layers. The ceramic TBC microstructure is controlled through selection of deposition technique and parameters. Typical processing approaches include plasma spray techniques employing powder, suspension, precursor solution feedstocks (APS) or a combination thereof, and electron beam–physical vapor deposition (EB-PVD). Understanding the high-temperature degradation mechanisms in advanced materials is fundamentally and critically important in developing strategies to enhance and predict component durability in gas turbine engines.[15,16]

The key drivers for both the metallic bond coat and the ceramic overlayer are shown in figure 8. For the metallic system, it is tailored to match the characteristics of superalloy and ceramic topcoat. Although the chemistry/phase composition determines the internal diffusion characteristics of the bond coat, the surface finish and plasticity dictate the mechanical bonding with the ceramic overlay. The oxidation reaction product plays an important role in bond coat/TBC adhesion, and hence, the thermally grown oxide (TGO) is expected to form slowly, readily, and continuously and is adherent to underlying bond coat.

For the ceramic overlayer, the interaction between bond coat and the surface characteristics (environment, temperature, etc.) play a critical role in downselecting chemistries. The time-dependent performance of the coat for a given bond coat temperature and surface temperature will evaluate the interaction between multiple failure drivers including sintering driven failure and also establish the oxidation and fatigue limit based on underlying bond coat characteristics. TBC thickness also plays a key role for addressing localized design requirements of components. The thickness of TBC can vary from 0.15- to 2-mm thick with turbine components between 0.15- to

FIG. 8 Key characteristics for (*A*) bond coat and its interactions with substrates and (*B*) TBC characteristics for system level temperature limit.



1-mm thick and combustion components from 1- to 2-mm thickness. Typically, the boundaries are defined using isothermal furnace testing and gradient high-heat flux testing for the particular TBC system.

Advances in metallic coatings are achieved by a systematic analysis of the failure behavior due to oxidation and TBC spallation times. The resultant optimized composition results in a significant reduction beta-phase (aluminum-reservoir) depletion in the bond coat, as shown in figure 9. This results in a reduced growth rate in the TGO, consequently increasing the oxidation protection of the metallic coatings. The selection and optimization of the appropriate composition depend on the substrate composition. Interdiffusion between the substrate and the bond coat and TGO growth both contribute to the rate of aluminum depletion from the bond coat.[17] Therefore, the right combination of superalloy/bond coat needs to be selected for maximizing the coating performance.

Existing TBCs are based on 8YSZ and are air plasma sprayed onto industrial turbine components. 8YSZ coatings are susceptible to sintering and phase instability when exposed to temperatures higher than 1,200°C. This results in an increase of the elastic modulus and also microstructural degradation of the ceramic. This increases the tendency for premature coating spallation. All the advanced low-thermal conductivity (low-K) compositions for superalloy compositions are typically coated with bond coats and tested for TBC spallation life both in isothermal testing and also under a thermal gradient, as shown in figure 10. Results from the aggressive thermal gradient testing showed that the spallation life for all the advanced compositions exceeded those of 8YSZ by at least a factor of 10. The spallation was improved primarily because of an increased sintering resistance of the advanced compositions.[18] The increased spallation life directly translates to an increased surface temperature limit of the TBC, consequently affecting the hot section component performance.

Environmental Effects

Modern gas turbines are operated with fuels that are very clean and within the allowances permitted by fuel specifications. However, the fuels that are being considered contain vanadium, sulfur, sodium, and calcium species that could significantly contribute to the degradation of components in hot gas flow path. The main potential risk of material degradation from these fuels is "hot corrosion" due to the contaminants listed here combined with alkali metal salts from ambient air. Both operating temperatures and pressure affect hot corrosion damage. The temperature range over which the hot corrosion occurs depends strongly on following three factors: deposit

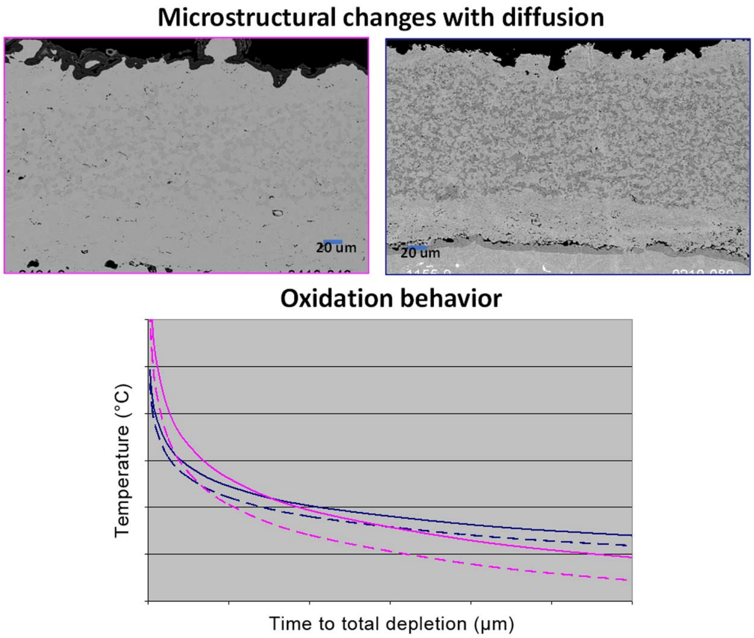
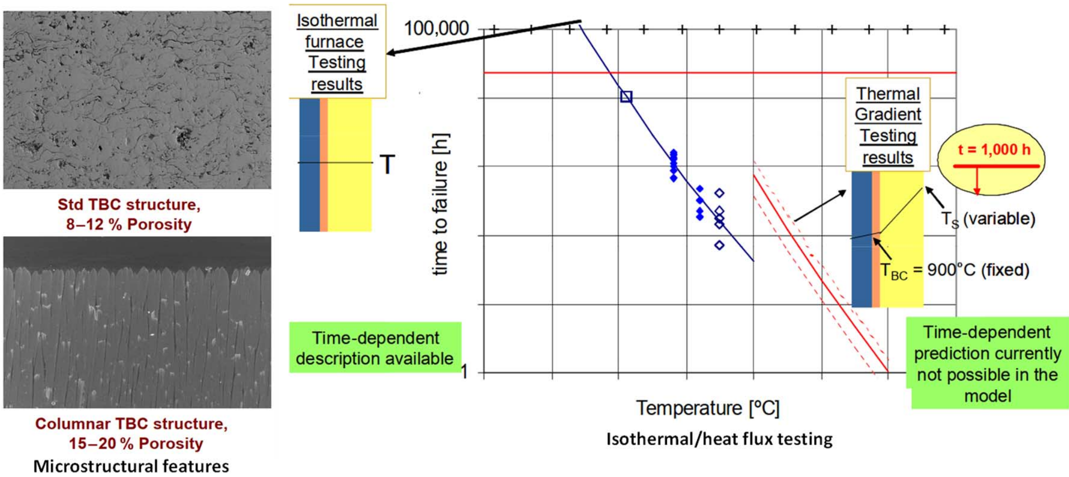


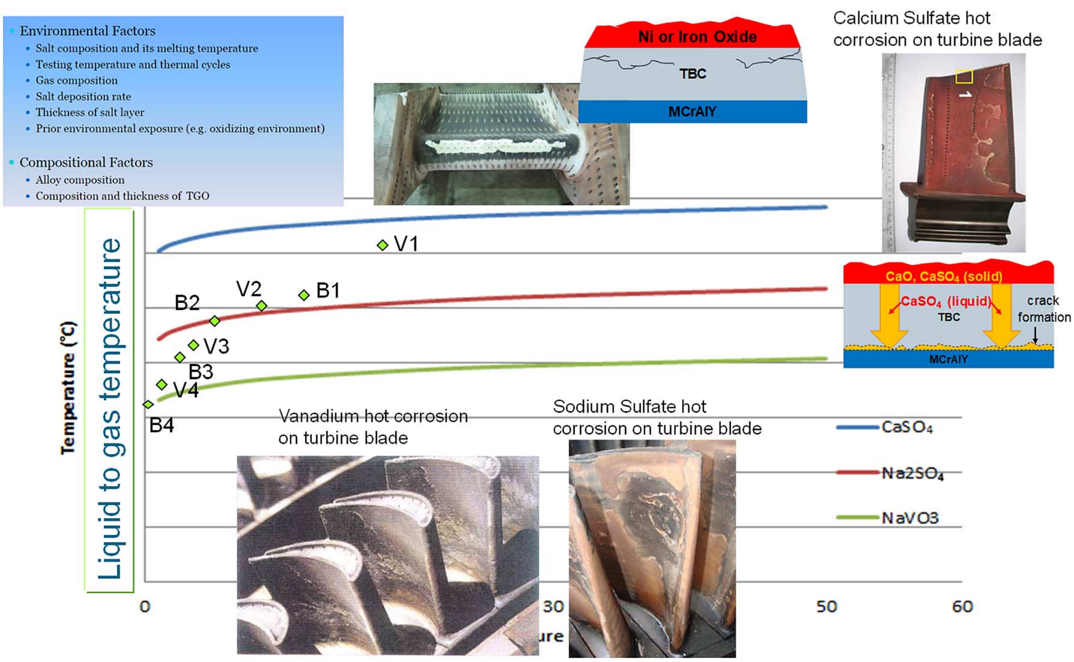
FIG. 9 Bond coats showing beta-phase depletion and corresponding oxidation curves.[17]

FIG. 10 Ceramic TBC characteristics and development using isothermal and gradient testing.



chemistry, gas constituents, and metal alloy (or bond coating/TBC composition). This establishes the need to develop advanced coatings capable for operation in multiple fuel environments, with a more detailed understanding of coatings failure mechanisms in complex fuel combustion environments. For the initiation of hot corrosion, deposition of the corrosive species, e.g., vanadates or sulfates, is necessary.[19] In addition to the thermodynamic stability, the condensation of the corrosive species on the blade/vane material is necessary to first initiate and then propagate hot corrosion. An assessment of component operating conditions and gas compositions throughout the hot gas paths, along with the observed hot corrosion reactions for a gas turbine, is shown in **figure 11**. The typical

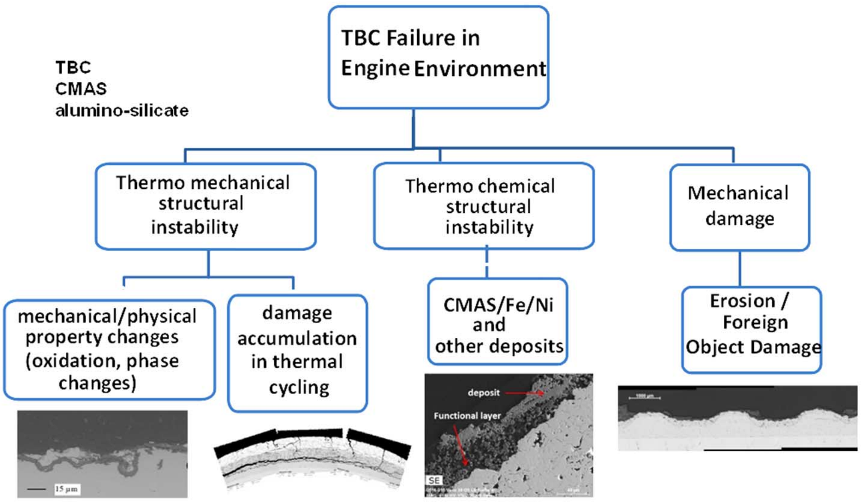
FIG. 11 Observed corrosion mechanisms correlated to component operating conditions.



temperature range for hot corrosion in gas turbines is 600°C–950°C. Multiple constituents lower the dew points for the corrosion regime. The dew point rises with increasing pressure, which leads to more surface areas with the risk of hot corrosion. The dew point curve depends on the composition of the fuel (carbon to hydrogen ratio), the amount of excess air, injected water, and the level of impurities such as sulfur, sodium, potassium, and chloride. The most critical reaction in the vanadate–sulfate hot corrosion of YSZ is $Y_2O_3(SS) + V_2O_5 \Leftrightarrow 2YVO_4(S)$. This reaction depletes the ZrO_2 matrix of the Y_2O_3 stabilizer and causes transformation of the zirconia from the tetragonal to monoclinic crystal structure, thus degrading the YSZ coating. A majority of the mechanisms observed show spallation of the TBC with surface-limited attacks with nickel/iron oxide deposition but a deeper interface reaction for liquid calcium-, sodium-, sulfur-, potassium-, and vanadium-based deposits.

Apart from fuel bound impurities, operational conditions such as surrounding environments (sand), filter clogging, or just operation at hotter temperatures also cause deposition on the surface of the TBCs. Although TBCs have been critical to the operation of gas turbines in aircraft and land-based applications providing thermal, oxidation, and hot corrosion protection of high-temperature components, reliability concerns over thermomechanical integrity of these coatings arise because of fine particle (calcium-magnesium-aluminum-silicate [CMAS]) ingestion when operated in a variety of environments ranging from volcanic zones to desert conditions. These TBCs are increasingly susceptible to degradation by molten CMAS deposits in advanced engines that operate at higher temperatures and in environments laden with ingestion of siliceous minerals (dust, sand, volcanic ash, runway debris) with the intake air. The ingested particles travel through the various engine zones, (1) the compressor blades, (2) the combustors, and (3) the turbine stages, where they either deposit on blades and vanes or block the cooling channels. At lower temperatures, these contaminants can cause erosive wear or local spallation of the TBC when impacting as solid particles. As engine temperatures increase, the siliceous debris adheres to the TBC surfaces and yields glassy melts that penetrate the TBC, leading to a loss of strain tolerance.[20] Firstly, when the CMAS becomes molten, its low viscosity enables its infiltration into the TBC intercolumnar gaps, porosity, and cracks; upon cooling, the melt freezes, and the infiltrated TBC becomes rigid, losing its strain tolerance. Delamination cracks can thus develop in the coating, leading to progressive TBC spallation during in-service thermal cycling. Secondly, a chemical interaction takes place between the molten CMAS and the top-coat ceramic, degrading the column tips and the porous morphology, especially in the upper part of the coating. The initially fine-scale intracolumnar porosity and the feather-like porosity are replaced by larger pores filled with CMAS.[21] This leads to spallation of the TBCs and hence, is detrimental to the structural integrity of the component, resulting in loss in power or catastrophic failures, as shown in figure 12.

FIG. 12 Observed TBC failure mechanisms in gas turbines.



AM

Although investment casting is the current production technologies for casting turbine components, faster design to manufacturing requirements are sought to meet the changing demands of today's power grid of improved efficiency through operating temperature increases, fuel flexibility, and reduced cooling requirements. Advances in multiple AM process can enable redesign of turbine components for extreme environments with the potential to reduce cost. AM is of particular interest to improve component functionality, higher temperature capability, and superior durability in turbine applications. AM methods have an immense potential to open up the design space by working directly with the 3-D model to produce near-net shapes and enable fast design–manufacturing iterations, thereby significantly reducing product cost and lead time up to 25 % from current baseline.

The technology to develop an integrated solution for design of components that is optimized for building via AM, that simulates performance of the design, and that provides the solutions to perform the AM setup, preparation, and validation is shown in figure 13. The automated calculations iterate until they create an optimized geometry. The resulting organic shapes are lightweight and optimally satisfy performance requirements. Advanced capabilities exist to verify the impact of AM processes and to validate that the printed parts will perform to target design requirements. This integrated solution enables accurate and efficient design, simulation, and optimization to ensure the new design meets performance requirements.

There is a growing need to upgrade existing engines to reach >65 % efficiency. This translates to increasing operating temperatures, resulting in demand for advanced designs and improved materials/manufacturing developments. AM processes provide means for material developments to be married with advanced design strategies to realize the needed improvements at a reasonable cost. Figure 14 shows a blade profile with novel

FIG. 13 End to end solution for design for AM.

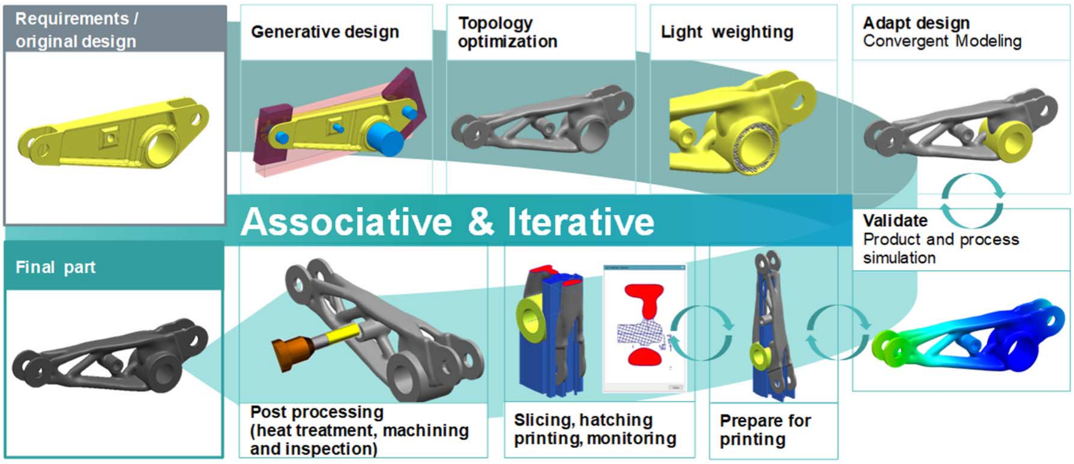
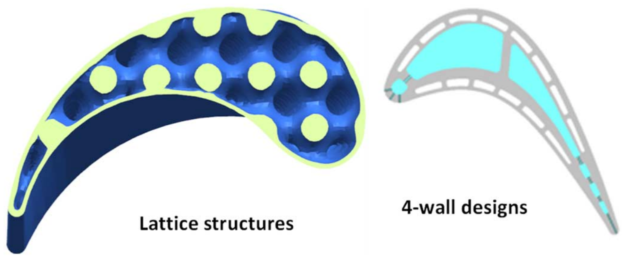


FIG. 14 Cross-sectional view of advanced designs created within airfoil geometry of turbine blade.



concepts for cooling, combining multiwall concepts with lattice structures to develop innovative designs of the internal cooling circuit. Multiwall designs, however, are hard to realize in practice because of the high stresses building up as a result of large thermal gradients between the hot airfoil and the cooler internal walls. Multiwall designs reinforced with lattice structures (e.g., honeycomb structures) provide a solution to mitigate the stresses. In addition, lattice structures increase overall surface area and thereby contribute toward more efficient heat transfer from outer wall.

Figure 15 shows the details of the powder bed fusion AM process, taking the digital 3-D model to be build layer by layer to achieve the final blade geometry. The blade shown leveraged the capabilities available with a design for AM and implemented a completely revised and improved internal cooling geometry, which could only be manufactured using an AM process. Siemens achieved an industry breakthrough with AM produced gas turbine blades and successfully validated multiple AM-printed turbine blades with a conventional blade design at full engine conditions.[22] Components were tested at 13,000 rpm (216 Hz) and temperatures beyond 1,250°C to meet operational requirements of 1,000 mph (~450 m/s) rotation and load of 11 tons—twice the speed that a Boeing 737 can fly and approximately the weight of a fully loaded London double-decker bus.

AM has the potential to enable enhanced performance through cost-effective rapid redesign, remanufacture, and repair of critical components as shown in figure 16. Apart from efficiency/performance improvements via advanced designs, shorter lead/repair times are sought utilizing AM processing that enables fast design-manufacturing iterations for faster validation, thereby reducing lead-time up to 25 % from current baseline. Along with the potential benefits from this technology, the process-to-performance relationships are still under investigation. In particular, the issues of fatigue performance, including crack initiation and crack propagation of AM printed material, are not fully known.

PROGRESSIVE DEVELOPMENTS

Overall, a rigorous progressive testing and validation approach, shown in figure 17, provides a thorough understanding of component behavior and means for improving final system performance. This usually begins with a technology element level testing of superalloys, bond coats, and ceramic TBC, involving measurement of thermophysical and mechanical properties and evaluation of each, in the relevant conditions. Following this, a system-level bench test will be conducted, which includes a thermal gradient mechanical fatigue testing of coupons that have all the three layers—superalloys with novel structures, bond coat, and the TBC system.

FIG. 15 AM printing process to achieve complex turbine blades.

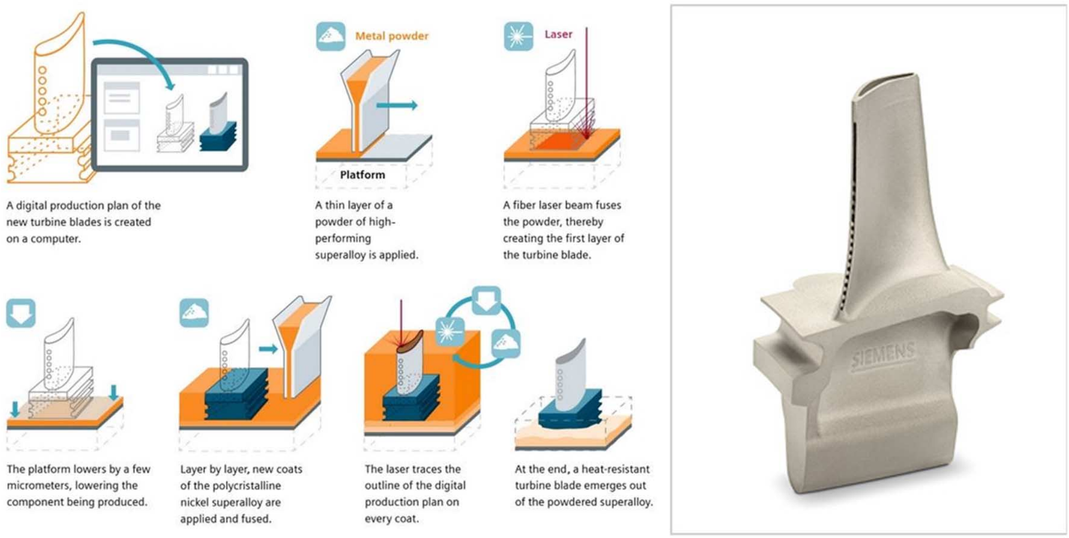


FIG. 16

Potential benefits of AM for gas turbine businesses.

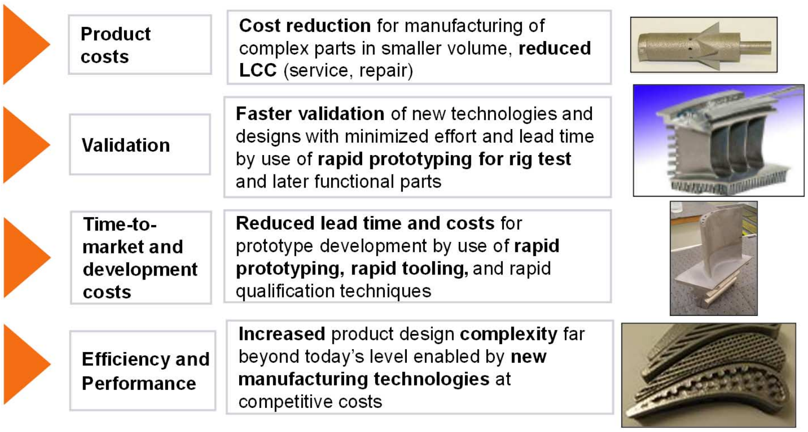
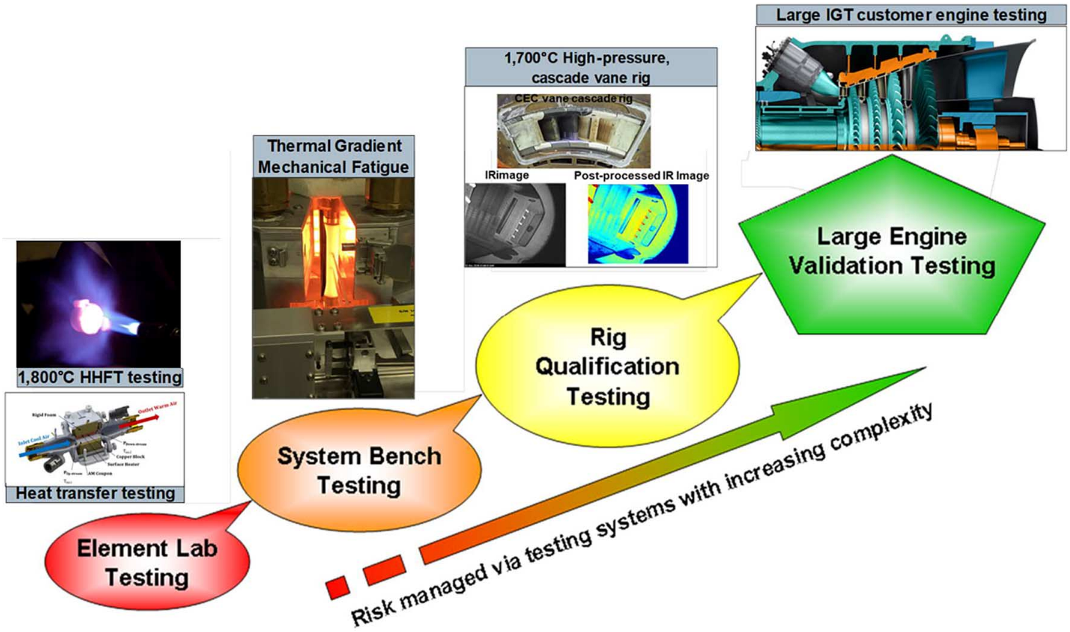


FIG. 17 Systematic technology testing and risk reduction approach, with a final validation test in a full engine test.



This will ensure that the TMF is within the range of cast failure data, considered acceptable for engine operation. This will minimize the risk for the next step of component-level testing in a gas turbine on a test bed, in which the realistic component geometry will be tested in high-pressure and high-gas-temperature engine-like conditions. The components will be instrumented with thermocouples, pressure taps, and observed via infrared cameras to for materials and design validation. After successful testing of the components on a test bed, these designs will be fleet released within new and upgrade-eligible gas turbines. This testing approach accelerates the technology development time from innovation to first engine verification for extreme environment materials and designs.

Conclusions

The paper discusses research needs for materials and coatings in extreme environments for industrial gas turbines. The push for higher firing temperatures, increased efficiency, and multifuel capability put a demanding requirement of these materials and coatings, and hence, a system-level integration of materials and advanced manufacturing solutions is needed. Because the combustor and turbine section is probably the most challenging environment in the gas turbine, the majority of research on reliability of protective coatings and novel component cooling designs, enabled by AM of nickel-based superalloys, is aimed to meet their design targets. The complex evolution of microstructural changes and its resultant effect on thermal and mechanical properties of superalloys needs to be understood to reliably predict component life. Advances in metallic and ceramic coatings are achieved by systematic evaluation of changes in thermomechanical properties along with deep understanding of the oxidation/strain-dependent failure mechanisms. The impact of fuel bound corrosive species along with fine-particle ingestion in desert conditions is presented, resulting in spallation of the coatings and detrimental impact on the structural integrity of the turbine front stage components. The potential of AM to open up the design space to improve component functionality and enable fast design–manufacturing iterations to reduce cost and lead time is presented. Finally, the need for a rigorous progressive testing and validation approach to provide a thorough understanding of component behavior and means for improving final system performance is shown to accelerate deployment of novel technologies.

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